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The Origin and Evolution of the Zodiacal Dust Cloud

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ABSTRACT

We have now analysed a substantial fraction of the IRAS observations of the zodiacal cloud, particularly in the 25 μm waveband. We have developed a gravitational perturbation theory that incorporates the effects of Poynting-Robertson light drag (Gomes and Dermott, 1992). We have also developed a numerical model, the SIMUL model, that reproduces the exact viewing geometry of the IRAS telescope and calculates the distribution of thermal flux produced by any particular distribution of dust particle orbits (Dermott and Nicholson, 1989). With these tools, and using a distribution of orbits based on those of asteroidal particles with 3.4 μm radii whose orbits decay due to Poynting-Robertson light drag and are perturbed by the planets, we have been able to: (1) account for the inclination and node of the background zodiacal cloud observed by IRAS in the 25 μm waveband; (2) relate the distribution of orbits in the Hirayama asteroid families to the observed shapes of the IRAS solar system dustbands; and (3) show that there is **observational** evidence in the IRAS data for the transport of asteroidal particles from the main belt to the Earth by Poynting-Robertson light drag.

INTRODUCTION

We need to know the origin of the particles that constitute the zodiacal cloud: are these particles predominantly cometary or asteroidal? Interplanetary dust particles (IDPs) are collected in the Earth's upper atmosphere and returned to Earth for analysis. However, because these particles are collected only after atmospheric braking, all knowledge of their interplanetary orbits is lost. Fortunately, there are other sources of information.

The Infrared Astronomical Satellite (IRAS) has provided us with our most detailed view of the zodiacal cloud. It is now known that the cloud is not featureless: IRAS discovered circumsolar near-ecliptic bands of dust that appear to be related to the prominent Hirayama asteroid families (Dermott and Nicholson, 1989) suggesting that the asteroid belt as a whole is a significant source of IDPs. We consider that the high quality of the IRAS observations, particularly those in the 25 μm waveband, requires a new approach to the modeling of the zodiacal cloud. The approach that was started at Cornell University by Dermott and Nicholson (1989), and is now being pursued at the University of Florida, is the subject of this short note.

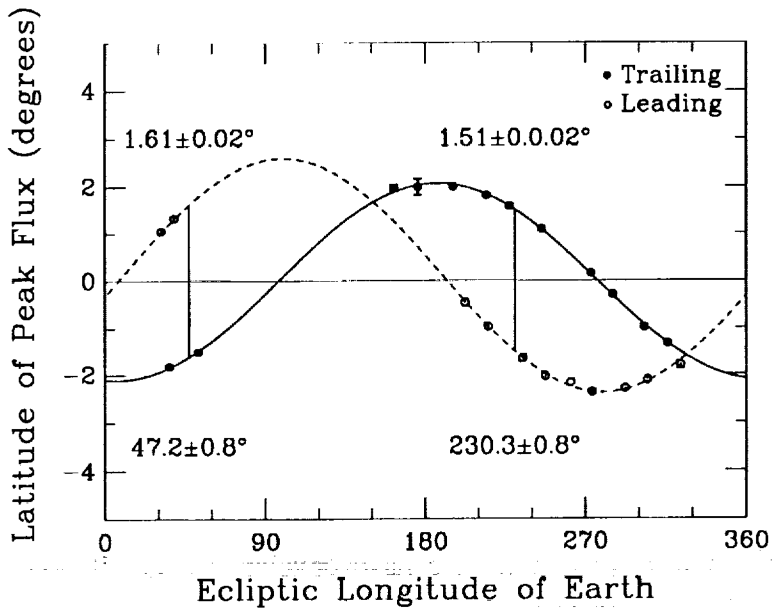

Figure 1. Variation of the ecliptic latitude of the peak background zodiacal emission with the position of the Earth observed by IRAS in the 25 micron waveband at an elongation angle of 90 degrees in either the leading or trailing directions. The numbers and vertical lines refer to the inclinations and the ascending and descending nodes of the cloud.

MODELING THE ZODIACAL CLOUD

Most previous attempts at modeling the zodiacal cloud have been based on finding a distribution of particle number density $n(\mathbf{r})$, where $\mathbf{r}$ is the heliocentric position vector, that satisfies the various observations. The number density function is not derived from first principles, rather it is usually assumed to have the form

$$n(r, \beta) = n_o(r/AU)^{-\nu} f(\beta)$$

where n_o is the particle number density at Earth orbit and β is the heliocentric latitude (Giese and Kneißel, 1989). The models are heliocentric and rotationally symmetric and do not distinguish between the plane of symmetry of the cloud and that of the ecliptic. We consider that the quality of the new spacecraft observations (see Fig. 1) demands an approach that is both more direct and more physically meaningful.

Our approach is to start with a postulated source of particles, either asteroidal or cometary, and then describe:

- the size-frequency distribution of the particles and its variation with distance from the Sun (Gustafson *et al.*, 1992; Durda *et al.*, 1992)
- the thermal and optical properties of the particles and their variation with particle size (Gustafson, 1992)

- the orbital evolution of the particles due to Poynting-Robertson drag, using equations of motion that include light pressure and gravitational perturbations (Gomes and Dermott, 1992).

Once the structure of the cloud has been specified in terms of the distribution of orbital elements and the distribution of particles on the orbits, we need a means of viewing the model cloud and comparing the predicted fluxes with the observations. We have constructed a three-dimensional numerical model (the SIMUL model) that calculates the distribution of flux produced by any particular distribution of dust particle orbits. This model reproduces the exact viewing geometry of the IRAS telescope and allows for the eccentricity of the Earth's orbit. The result is a model for the variation with ecliptic latitude of the brightness observed in a given waveband as the line of sight of the telescope sweeps through the model cloud at a constant elongation angle.

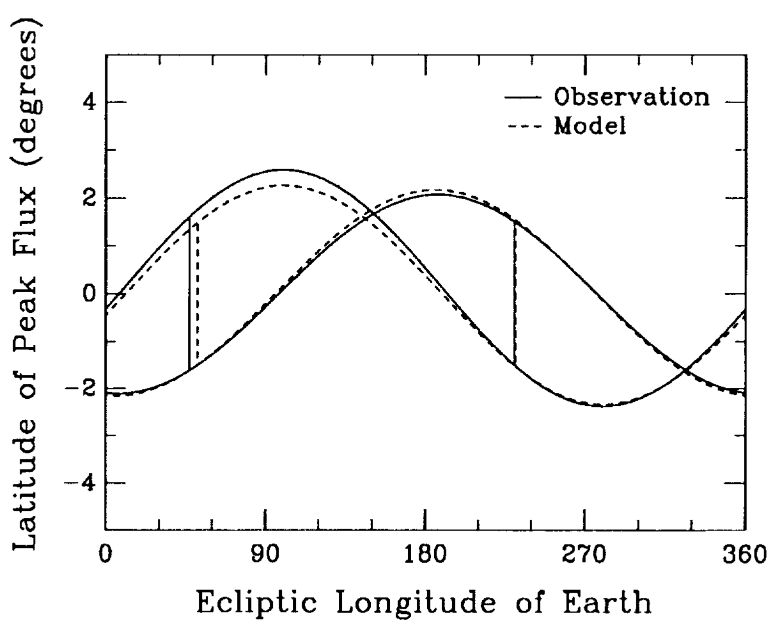

Figure 2. Comparison of the IRAS observations shown in Figure 1 with our model of the cloud based on asteroidal particles of 3.4 micron radii whose orbits decay due to PR drag.

Because the IRAS data set has given us precise information on the various asymmetries of the cloud, both those of the background (Fig. 1) and those associated with the dustbands, and because of the known association of the Hirayama asteroid families with the IRAS solar system dustbands (Dermott and Nicholson, 1989), our initial emphasis has been on the dynamical evolution of asteroidal particle orbits, but future work will include cometary orbits. Flynn (1992), at this meeting, reported on his analysis of the atmospheric heating of large micrometeorites and concluded that survival without melting demands a low relative velocity and that this favors an asteroidal source. Grün (1992), also at this meeting, reported that measurements by the Galileo and Ulysses spacecraft of the variations of the dust particle fluxes with the orientations of the detectors indicate that the dust particle orbits are more consistent with an asteroidal than a cometary source. Schramm *et al.* (1989) analysed 200 interplanetary dust particles and concluded that 45% are probably cometary but 37% have characteristics (chemical alteration by liquid water) that suggest an asteroidal origin. Thus, it is clear that both sources do need to be considered.

If the size-frequency distribution of the dust is a simple power law, then the effective area of the dust seen in a given waveband λ increases as the particle radii decrease until the absorption coefficient falls off to zero at some radius $\lesssim \lambda/2\pi$. Detailed calculations indicate that the flux in the 25 μm waveband should be dominated by that from particles of radius 3.4 μm (Gustafson, 1992) and, for ease of calculation, we assume here that all the particles in the cloud have that radius: future work will include more realistic size-frequency distributions. Predictions for a zodiacal cloud of particles that originate in the main asteroid belt and whose orbits decay due to PR drag are shown in Fig. 2. The agreement with the IRAS observations is remarkable.

Using the same tools, and making the same assumption about the dominant particle size, we have also been able to (1) relate the distribution of orbits in the Hirayama asteroid families to the observed shapes of the IRAS solar system dustbands; (2) show that there is **observational** evidence in the IRAS data for the transport of asteroidal particles from the main belt to the Earth by Poynting-Robertson light drag and (3) show that there is an albedo difference between the central, near-ecliptic bands and the "ten-degree" bands..

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